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Thermal Behavior of PM in-wheel Motor used in Off-road Motor Driven Truck

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Abstract

PM motor is an important energy conversion system for the off-road hybrid electric truck. The motor should be operated and delivered rated power to meet the driving requirement of the truck. For the permanent magnet is sensitive to the temperature variation, this paper presents the thermal behavior of the PM motor based on lumped parameter method. The heat flow caused by the conduction and convection in the PM motor are discussed, a thermal network considering the thermal resistance of the main components of PM motor is built and investigated. The steady-state and transient thermal analysis of the PM motor are calculated. The simulated results are validated with experiment measurement.

Keywords: permanent magnet motor, temperature distribution, lumped parameter method

1. Introduction

The off-road hybrid electric trucks are directly driven by the in-wheel motors. For the off-road dump truck driving with full load, it needs to overcome the larger driving resistance. When the truck running unload, the needed torque will be lower and the speed of truck will increase. PM motor has some characteristics, such as high torque/power density, wide constant-power speed range, it can meet the specific power requirement of off-road truck.

However, the permanent magnet in the PM motor is very sensitive to the temperature variation. The temperature of permanent magnet is important to the demagnetization capability. So, temperature rise is an important index to evaluate the performance of the PM motor. It is necessary to protect the permanent magnet from exceeding critical temperature to ensure the optimal use of the PM motor. The paper

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presents the thermal behavior of the90kW PM motor which used in off-road hybrid electric truck. A thermal model is built to describe the temperature evolutions of different parts of PM motor.

2. Thermal Modeling of PM Motor

The PM motor for the hybrid dump truck is of a great compactness and higher power. The most part of the electric power from the generator is used to driving the motor into rotation and moving the truck. The rest part of this energy will be heating up the motor, while these losses constitute the heating source of the PM motor: Joule effect in the windings of the stator, iron losses in the yoke and tooth parts of the stator, and partially into the magnets of the rotor, etc.

The PM motor includes two separate parts which is separated by a thin air gap (Fig.1(a)). The rotor is a freely rotating cylinder with the permanent magnets embedded into it. Its cooling is mainly performed by convection with the air in the gap and by conduction toward the shaft. The stator is a motionless assembly of silicon steel laminations with embedded windings. The most common way to analyze the cooling of a motor is to approximate the motor with a cylinder, and some papers [1,2,3,4] have reported forced convection around a cylinder. Heat flow between the winding, stator core, and shaft is illustrated in Fig.1(b). The red arrows mean the heat flow caused by conduction, and the green arrows represent the heat flow caused by the convective.

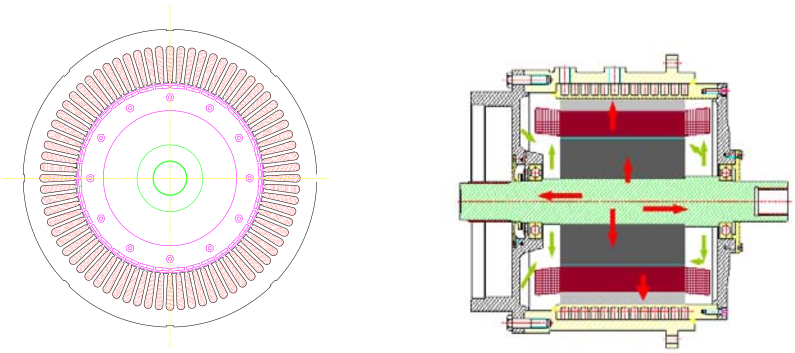


Fig.1 (a) Cross section of PM in-wheel motor (b) Heat flow in the motor

The main components and geometries of PM motor are shown in the Table 1.

Table 1. Specifications of PM Motor

Motor Parameters	Value	Unit
Nominal Power	90	KW
Nominal Continuous Torque	1100	Nm
Stator outer radius	222.5	mm
Rotor outer radius	141	mm
Rotor inner radius	50	mm
Air Gap	1.5	mm
Axial length of rotor core	300	mm
Slot Number	72	

2.1. Lumped Parameter Method of PM Motor

Lumped parameter method has been used to estimate the key temperatures of the motor. A lumped parameter thermal model is developed to analyze the heat transfer process in this PM motor. The nodes in the thermal network are separated by thermal resistance that represents the heat transfer between components of the PM motor. The thermal resistance is the thermal properties of the different materials used in the motor, usually due to conduction and convection of the components of the PM motor. The heat transfer by radiation is ignored in this model, for the temperature differences between surfaces inside the motor are small.

For transient thermal analysis, the thermal energy stored in a motor will vary with time. The thermal capacitance C can be used to account for the variation in the internal energy of motor components.

$$C = c_p \rho V \tag{1}$$

where, c_p is the specific heat capacity of the component material, ρ and V are the part's density and volume respectively.

The power losses in the motor, mainly the copper loss (P_{cu}) of stator winding and iron loss (P_{fe}), are represented as heat sources in the thermal network.

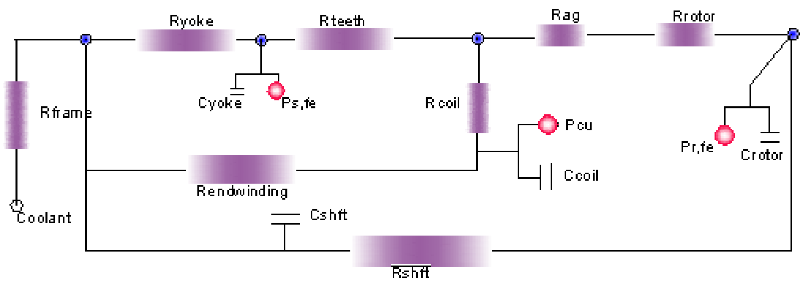


Fig.2 Simplified thermal network of PM motor

The heat flow in the PM motor is described in the thermal network shown in Fig.2. The node temperatures in the thermal network are defined as a set of heat balance equations, to estimate temperatures in each part of motor.

$$[C]\{\frac{dT}{dt}\} = [G]\{T\} + [P] \tag{2}$$

where, T is node temperature, the heat capacitance matrix [C] and thermal resistance matrix [G] can be derived from the dimensions, materials and thermal properties of the PM motor.

2.2. Thermal Resistance in the Thermal Network

As shown in Fig.1(a)(b), the solid components of the PM motor can be treated as the general cylindrical components. Assumption of the better thermal contact between components, the basic thermal network can be simplified as Fig.2. The symbols of R_{yoke}, R_{teeth}, R_{rotor} are the thermal resistances of stator yoke, teeth, and rotor correspondingly. They all can be calculated by the heat transfer equation of hollow cylinders (outer radius of cylinder r_1, inner radius of cylinder r_2).

$$R_{hc} = \frac{1}{2\pi\lambda L}\ln(\frac{r_1}{r_2}) \tag{3}$$

1) The thermal resistance of shaft

The motor shaft is modelled as a cylinder without heat generation. The axial heat conduction of motor consists of three sections.

$$R_{shft} = \frac{1}{2\pi\lambda_s L_s}\ln(\frac{r_{or}}{r_{ir}}) + \frac{1}{4}(\frac{0.5L_s}{\lambda_s \pi r_{ir}^2}) + \frac{1}{2}(\frac{0.5(L_{shf}-L_s)}{\lambda_s \pi r_{ir}^2}) \tag{4}$$

where, the shaft length L_{shft}, the thermal conductivity of shaft λ_s, L_s axial length of rotor core, the outer radius of rotor r_{or}, the inner radius of rotor r_{ir}.

2) The thermal resistance of air gap between the stator and the rotor

The air-gap exists in the PM motor between the stator and rotor, while one of cylinder (rotor) rotating inside a static one (stator). The air flows axially in the air-gap along the rotor core length. The stator has 72 axial slots equally distributed on its inner surface, where the rotor has smooth outer surface for the permanent magnet embedded in it. So, the thermal resistance of air gap between the stator and the rotor is composed of three sections: the convective heat transfer between the stator and the air gap, the conduction resistance of the air gap, and the convective heat transfer between stator and air gap.

$$R_{airgap} = R_{s-a} + \frac{1}{2\pi\lambda_{ir} L_s}\ln(\frac{r_{is}}{r_{or}}) + R_{a-r} \tag{5}$$

where, R_{s-a} is the convection thermal resistance between the stator and air gap, R_{a-r} is the convection thermal resistance between air gap and rotor. All these two items can be defined as:

$$R_a = \frac{l_{air}}{Nu\lambda_{air} A_{air}} \tag{6}$$

where, l_{air} is the radial length of air-gap, Nu the Nusselt number, A_{air} the average area of the air gap along axial direction.

The flow pattern in the air gap can be judged from the Taylor (Ta) number.

$$T_a = \mathrm{Re}(\frac{l_{air}}{r_{or}})^{0.5} \tag{7}$$

$$\begin{aligned} Nu &= 2 & T_a &< 41 \\ Nu &= 0.202 T_a^{0.63} P_r^{0.27} & 41 < T_a &< 100 \\ Nu &= 0.386 T_a^{0.5} P_r^{0.27} & T_a &> 100 \end{aligned} \tag{8}$$

3) The heat transfer between the end winding and case

$$R_{ew} = \frac{1}{2\pi\lambda_{air}(L_{oc}-L_s)}\ln(\frac{r_{oy}}{r_{oy}-\alpha l_{sy}}) \tag{9}$$

where, L_{oc} external case length, r_{oy} outer stator yoke radius, l_{sy} stator yoke height, α reduction coefficient.

3. Thermal analysis of PM motor

3.1 Steady-state Temperature of PM Motor

Based on the nominal power of the PM motor, the total stator iron losses was assumed as 2750W, where the copper losses of stator winding was 1550W (at the nominal current), and the iron losses is about 1200W (at the nominal speed). The volume flow rate of the cooling water in the spiral duct was set as 18L/min, temperature:21^{0}C（input port）. The flow pattern of the cooling water was turbulent flow based on the dimensions of the duct. The temperature distribution within the motor by PWM waveform was calculated as: case: 49.8^{0}C, stator yoke: 55.6^{0}C, stator teeth: 66^{0}C, end windings:92^{0}C

3.2 Thermal Transient analysis of PM Motor

Transient thermal model was used to simulate the motor during the long operating period of truck.

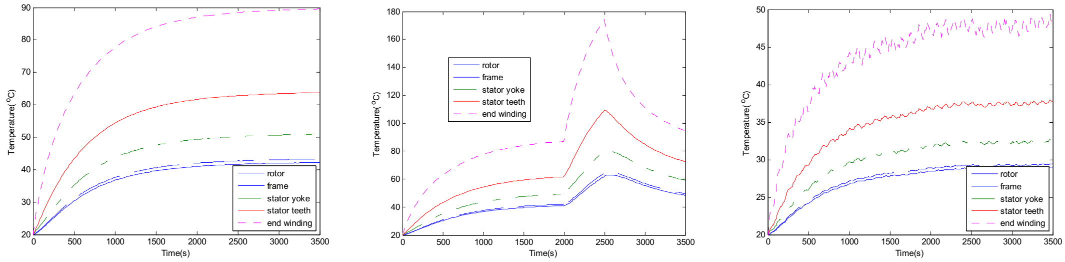


Fig.3 Transient simulation temperature response of the PM motor

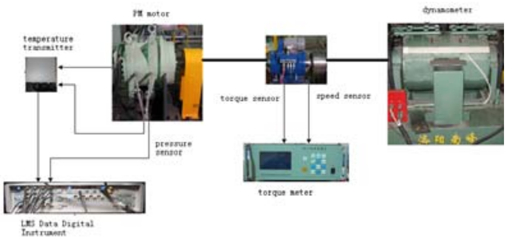
(a) long period (b) with overloaded power (c) at the intermittent operation

The simulation results show the variations of the temperature at the main components of the PM motor, according to the copper losses (1550W) and the iron losses (1200W) injected in the motor. The maximum temperature of the end windings for this simulated status is about 89 °C. The temperatures of the components (Fig3(a)) are met with the requirement of the F protection class of motor.

For the motor-driving truck always operates in the extreme condition, the motor load will vary correspondingly. Fig.3(b) shows the calculated thermal response when the PM motor overloaded 3 times the nominal power during the 2000s-2500s. Fig.3(c) shows the temperature evolution of the components in the PM motor at certain duty cycle of the truck. The temperatures of components are lower than the temperatures with the motor at constant power value.

4. Experiment and Testing of PM Motor

The experiment equipment has been built to drive PM motor (shown in Fig.4). A frequency converter connects the power supply and the motor in order to control the motor operating. The frequency converter can change the frequency input to the motor. The temperature variation was achieved in the case of motor operating at the constant load.



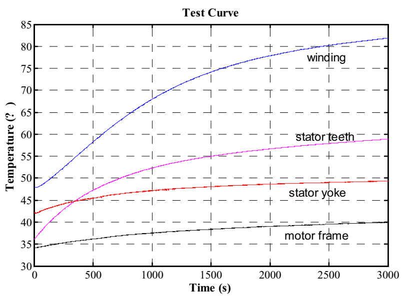


Fig.4 Test bench of PM motor

Fig.5 Test temperature response of the PM motor at current 160A

The experiment rig was configured to measure and recorded the temperatures of stator windings, stator yoke, stator tooth, and values of the input phase current, the output power of motor. Three sensors have been positioned on the external connections of each phase of the stator end windings. In order to measure the maximum temperature of the motor, the six thermocouples (PT100) were attached on the stator upper side surface of the motor. Three of thermocouples were used to measure the temperatures of yoke, the others for measuring the temperature of stator tooth. The input to the system is a 3 phase AC voltage which produces the current to meet the torque demand. The testing torque is set at a continuous torque of 867Nm for 3000 seconds. The motor controller is designed to regulate the voltage and current supplied to the motor to achieve the set torque. The output power of motor is about 90kW at 983rpm the rotation speed of the motor. The volume flow rate of cooling water is 18L/min.

All the temperature values were recorded by the LMS data digital collector simultaneously. The sampling time has been set to 0.5s to achieve a high accuracy of measurements.

Fig.5 has shown that the temperature evolution in different regions of the PM motor varying with time. The temperatures of components were not the same ones at the initial time, this is because that the temperatures were collected after the motor has been working for a little time. The results obtained by the experiment measurement (Fig.3) were compared to results calculated by lumped parameter model (Fig.5). A similar trend of the temperature rise profile can be observed between them. The simulation temperatures of transient analysis were a little higher than the measured ones. These differences were mainly due to the fact that constant convection and radiation heat transfer coefficients values were used in the model, the losses were assumed constant with time, and some mechanical losses of motor were denied.

5. Conclusions

PM motor has been required to met thermal constrains in the process of different working conditions. The thermal analysis of the PM motor for the off-road hybrid driving vehicle was investigated using the lumped parameter method. The thermal resistances and capacitances in the thermal network were calculated based on the geometries of the motor. Good agreement between simulation and experimental results has been obtained when the motor is operating at transient operating conditions. The lumped parameter method can be used to estimating the temperature variations of motor quickly and accurately.

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